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Review Article

Range-Anxiety Reduction Strategies for Extended-Range Electric Vehicle

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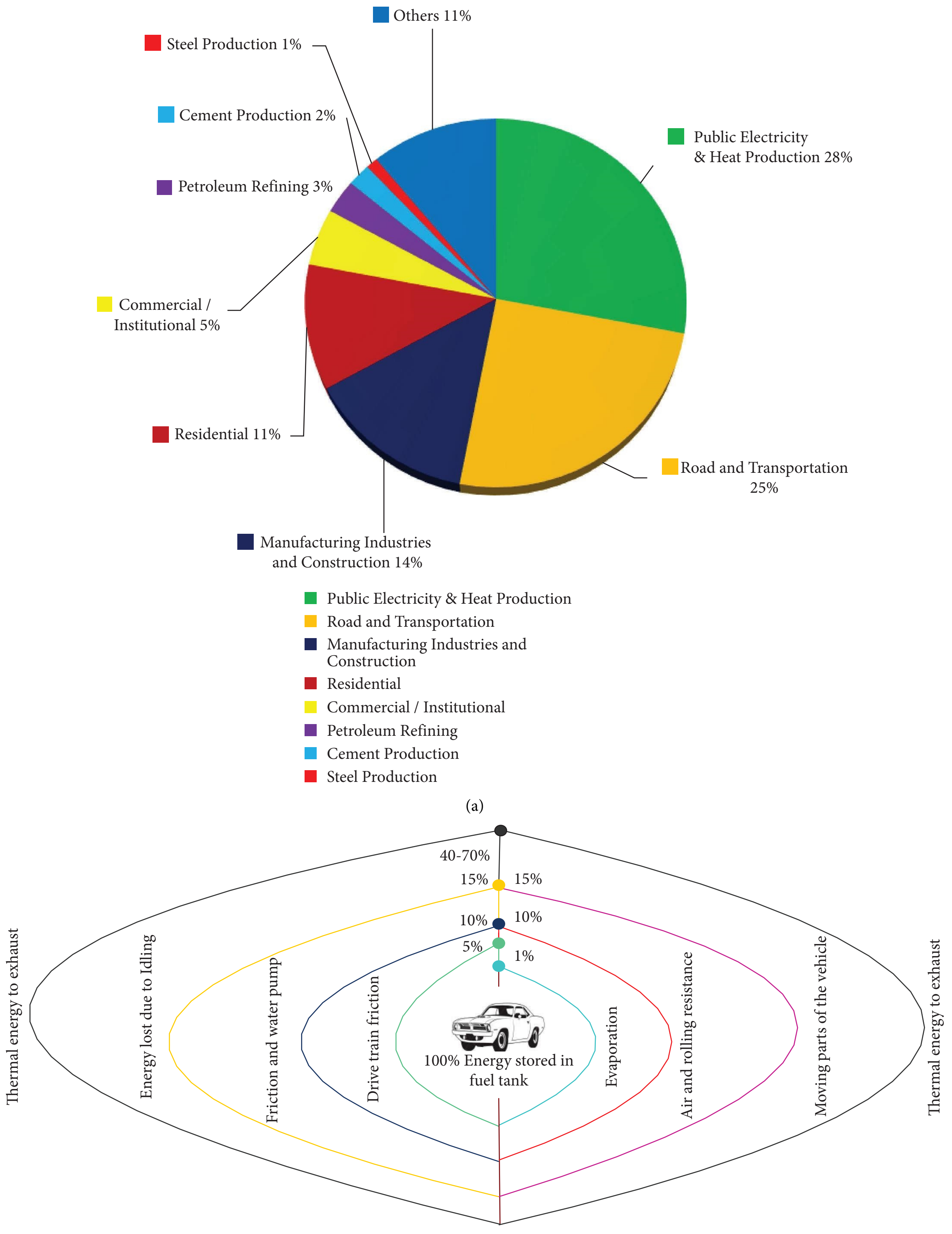
Transportation is the leading source of logistics, and people contribute the significant primary emissions for increasing global warming, so we should avoid such a situation and concentrate on zero emissions. The range of the vehicle is the major problem (range-anxiety) in electric vehicles. Nowadays, researchers focus on range extender optimization since range extenders significantly improve the range of the vehicle with an auxiliary power unit (APU), which can prove consumer satisfaction. However, range extenders can recover energy by proposing the various configurations and systems of extended-range electric vehicles (EREV). Many industries and researchers summarize these efforts to optimize and find the solution for range-extenders. This paper reviewed the most suitable technologies for energy recovery and state-of-the-art topological constructions. The analysis of the study primarily concentrated on optimizing the cost of the systems, fewer emissions, and more fuel economy. The research is based on the range-extenders evaluation and summary for electric vehicles to guide automakers and researchers to invent other state-of-the-art configurations and topologies to obtain optimized EV ranges, namely, enhanced functionality and fewer emissions. A survey on specific extend-range electric vehicles and classification of EREV technologies, the performance of APUs, different control strategies of energy management in EREVs, and various existing difficulties are discussed and further enhanced for the future researcher EREV forecast offered by advanced technologies.

1. Introduction

Road transportation accounts for over 75% of total energy loss in the transportation industry; people and logistics can move around more efficiently with a well-designed transportation infrastructure [1]. The automotive industry has played a significant part in building human civilization, and its economic prosperity has had a long-term impact on pollution levels [2]. Internal combustion engines (ICE) are responsible for 20%–30% of total greenhouse gas emissions (Figure 1(a)) [5]. The greenhouse effect caused by the internal combustion engine uses the ideal gas law, which significantly impacts human health by releasing harmful gases NO_2, CO_2, CO, and NO [1]. Friction and heat loss on the moving component cause ICE vehicles to lose energy. Figure 1(b) shows ICE's energy flow diagram [4]. In this sense, replacing internal combustion engines raises the priority of electric vehicles (EVs) as the best option for emission reduction [6].

In 1834, an earlier development of electric vehicles ran by tricycle power; however, ICE vehicles now account for the majority share in the market [8].

The propulsion of battery-powered electric vehicles necessitates a large battery pack with a limited driving range [9]. Creating a hybrid electric vehicle, which combines an internal combustion engine with an electric motor, is best to increase power and reduce pollution [10]. Hybrid electric vehicle (HEV) promises higher fuel efficiency than ICE vehicles and preserves their state of charge (SOC) during the journey [11]. They achieved zero emissions by utilizing advanced, highly efficient power train technologies, the battery, and hybrid electric vehicles [12]. As a result, the automobile industry chooses to shift to EV power trains; based on this, the shipment progress is rising in the EV and



(a)

(b)

FIGURE 1: (a) Greenhouse gas emissions sector according to the European environmental agency (EEA) inventory report 2019 [3]. (b) Energy flow diagram of an internal combustion engine [4].

HEVs, with projections based on the International Energy Agency (IEA) report ensuring significant growth as shown in Figure 2 [2, 7].

Regenerative braking and the fuel system are critical issues with HEVs. Plug-in hybrid electric vehicles address this problem, with the battery pack charged via external outlets [13]. Unlike HEVs, plug-in hybrid electric vehicles (PHEVs) allow for an electric motor as the primary mode of propulsion, with an ICE as a backup. When the battery SOC exceeds the limit, the PHEV becomes an HEV with ICE as the primary power source [14]. PHEVs solve the problem of limited driving range while also providing V2G capability [10]. However, due to limitations in energy storage technologies, battery electric vehicles (BEVs) cannot provide consumers with a good driving range [15]. The demand and necessity of range extenders play a significant role in long-driving range electric vehicles with a secondary onboard auxiliary power unit and rechargeable battery pack to overcome range-anxiety issues by providing a continuous supply throughout the trip. The electric motor drives the EREV wheels. APUs typically use a fuel combustion engine and a generator (a generator that includes an integration with the starter is familiar as an ISG). Still, recent investigations have shown better performance in producing electricity with the hydrogen (H_2) fuel cell system [16–19]. A higher degree of electrification and better control strategy is designed and available in EREV due to the compact size of APU compared to the series of plug-in hybrid electric vehicles [20]. Advanced forms of APU, in particular, are being investigated based on energy theory. The gas turbine system is developed by Bou Nader et al. Various comparisons with other type of electric vehicle, Provides in [21–23].

The final output of ISG transfers electrical energy from mechanical torque to chemical energy. An APU will act as a bypass auxiliary device and provide a balanced power supply when the battery SOC is below a certain point. Sometimes, a series of hybrid electric vehicles with the plug-in behaves as an EREV by meeting all the power demand requirements [24, 25]. Engine configuration, energy storage system (ESS) charging logic, power train structure, and relative battery size, vary for instance [26–33]. Table 1 shows the powertrain of different vehicles with variants. Lately, in the electric vehicle industry, EREV is one of the essential platforms [37, 38]. The electric vehicle manufacturers have implemented an application for EREV, and products such as the Chevrolet Volt, Nissan e-Power, and BMW i3 REx have gotten much attention [39, 40]. The extended van Ford Transit hybrid range provides a reliable alternative for city driving logistics [41]. According to research, an energy management system depends on the capacity and size of an energy storage system of an EREV [42]. The battery capacity depends based upon the selection of the appropriate engine. The EREV's operating characteristics, power handling capacity, energy management, and performance depend upon every component, to maintain balanced power by adjusting the objectives of dynamic programming [43–45].

Recent research has focused on APU charging control optimization and EREV energy management [46–50]. For instance, some researchers discovered that rule-based methods are unsuitable for various driving patterns used in the control system; alternatively, optimal solutions are considered for Energy Management System (EMS) [31, 51–53]. These issues can improve or be solved with a few references. This paper shows power management and APU charging control strategies for electric vehicles.

The remaining paper organizes the following sections. Section 2 introduces the electric vehicle technology with the state-of-the-art extended-range electric vehicle. However, Section 3 provides the technological comparison of EREV. Furthermore, Section 4 discusses the widely used control strategies and methods compared to EREV. Furthermore, Section 5 then delves into the APU charging control strategies for EREV energy management in depth. Section 6 examines a case study of a typical EREV model. Finally, this paper concludes with Section 6. Modern EREV structures and novel optimized EMSs are the future development of knowledge and inspiration.

2. Electric Vehicle Technology with the State-of-the-Art Extended-Range Electric Vehicle

The range extender (RE) consists of an auxiliary power unit (APU) and can be operated with a satisfactory solution to extend the EV's autonomy. An engine with an external or internal combustion engine and a generator are the primary components of the range extender (RE). The main function of a RE is to improve the mileage of electric vehicles. If the battery's state of charge (SOC) is below certain boundary conditions in the operation of the driving mode, the vehicle operation is continuous throughout by recharging the vehicle's battery. The significant comparison between the PHEV and EREV is that the motor always propels the wheels. In the depletion mode of operation or to drive the vehicle, the generator recharges the battery [54]. An APU is configured with the series configuration and will act as the primary system. The interconnected subsystems are the electric motor, electronic management, battery, and generator. To maintain the optimal functioning of the controller in electronic and mechanical power obtained from the battery and the electrical energy converted from the electric motor, the EREV consists of two basic modes of operation, namely, an extended-range mode of operation and a pure electric vehicle, where the distance is longer for an extended-range electric vehicle, and the distance is shorter for a pure electric vehicle mode of operation.

In the vehicle, the SOC of the battery is below a certain level, and the pure electric vehicle mode of operation is continuous. The function of RE depends upon certain boundary conditions of the battery and the functioning maintained by the power manager.

An energy flow configuration as shown in Figure 3(a) charge sustain period and (b) depleting period, forthcoming EVs overcome various social and technical challenges over ICE vehicles. Compared to the ICE vehicles, the electric vehicle's driver faces range-anxiety problems due to the shorter driving range. The range-anxiety stock is limited in the present batteries (0.565 MJ/kg–Li-ion

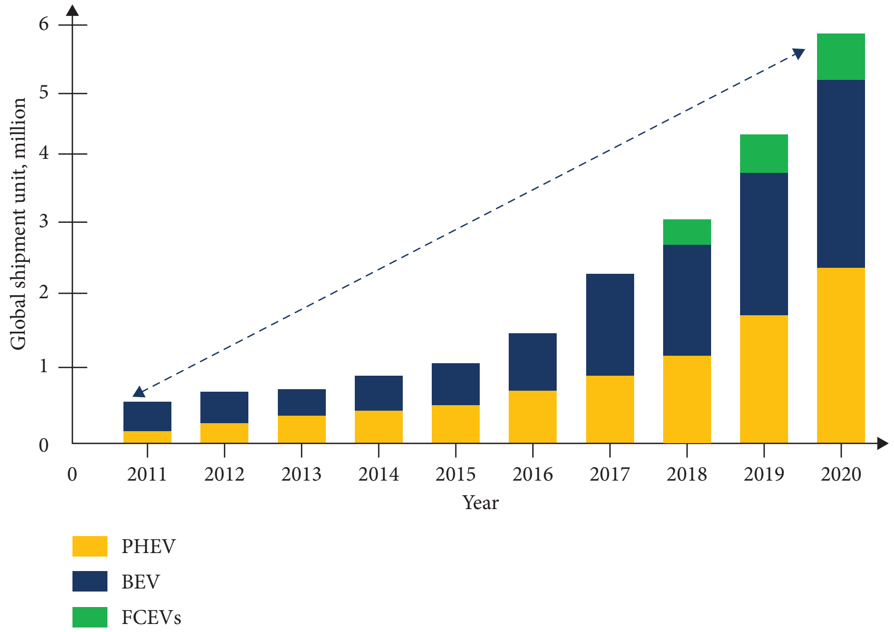


Figure 2: Global EV/HEV shipment estimates [7].

Table 1: Comparison of alternative vehicle configurations with various powertrain models.

Model	ICEV [34]	Parallel [20]	Series-parallel [28]	EREV [34]	BEV [35]	Series [20]	PHEV [36]
Range	√√	√√	√√	√√	√	√√	√√
Performance	√√	√	√	√√	√√	√	√
Electric-motor	0	1	2	2	1	2	2
Battery capacity	—	√	√	√√	√√√	√√	√√
Engine efficiency	√	√√	√√	√√√	—	√√	√√
Power train complexity	√	√√	√√√	√	√	√	√√
Transmission of engine	1	1	1	0	0	0	1

battery); fossil fuel energy density is compared to (43.48 MJ/kg) [55].

2.1. Technological Categorization of EREV. An electric propulsion system plays a vital role in an EREV. The main parts are the propulsion (or) transmission system, wheels, and the electric motor drive. The classification of electric motors is of three types, namely, in-wheel, alternating, and direct current. The significant following are the needs of an EREV motor:

(1) The density of power and power instant is very high.
(2) The consumption power is very high at high speeds and then cruising. For low speed maintenance, starting and climbing need high torque.
(3) Constant torque and constant power regions achieve a substantial range of speed.
(4) Torque response is very high.
(5) A range of torque and significant speed obtain high efficiency.
(6) The dynamic operating conditions of the vehicle achieve high robustness and more reliability.
(7) The cost of the motor is reasonable.

2.1.1. Extended Range Internal Combustion Engine (ER-ICE). The main parts of the range extender are a permanent magnet synchronous generator, an internal combustion engine, and a fuel tank [17, 46, 55–82], as shown in Figure 4. This type of structure is unsuitable for coupling between the RE and wheels. Only the vehicle output power fills the need to drive and needs a solid cut-off point to meet the traction characteristics of the vehicle. On the other hand, RE is to maintain the region of high frequency [80]. Another alternate solution is that many studies concentrated on reducing pollution levels, such as diesel [83] and natural gas [25].

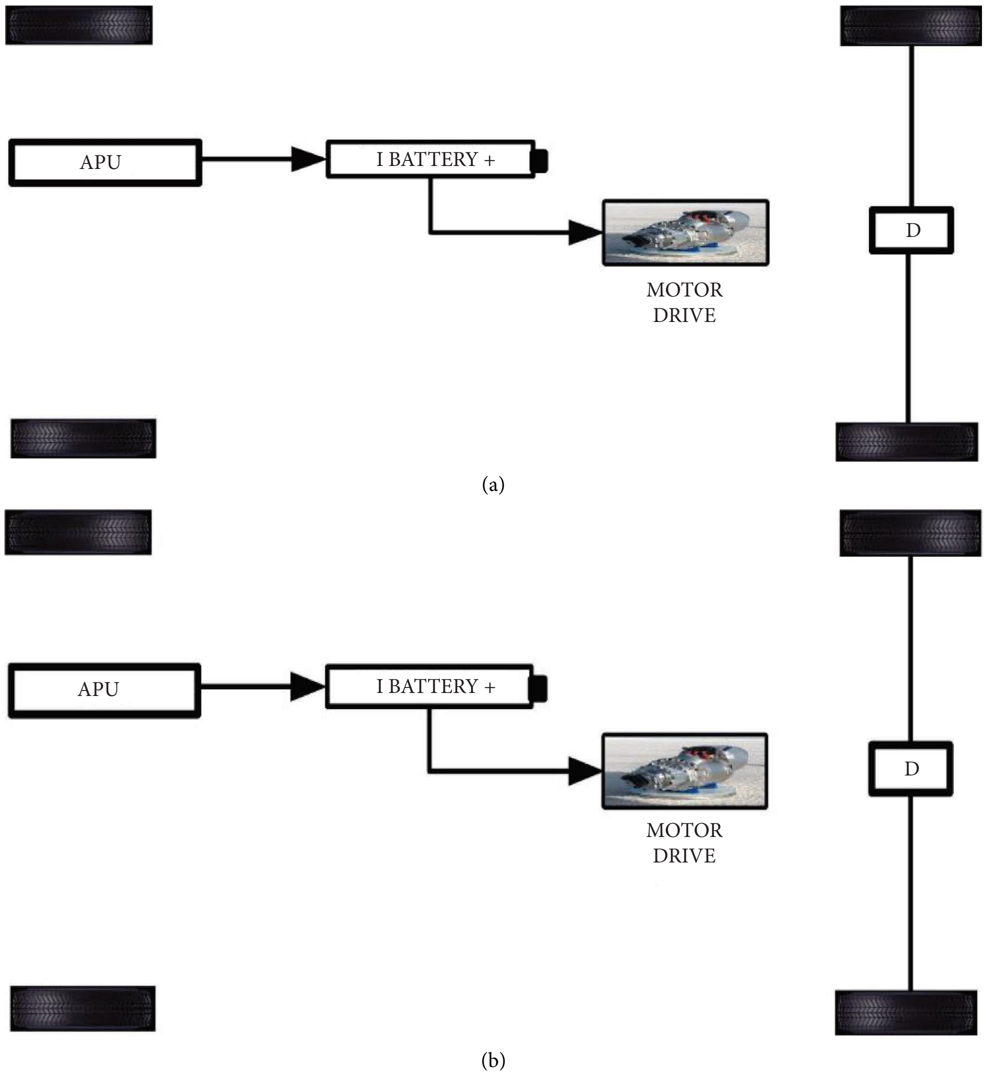


Figure 3: An EREV energy flow configuration; (a) charge sustaining period; (b) charge depleting period.

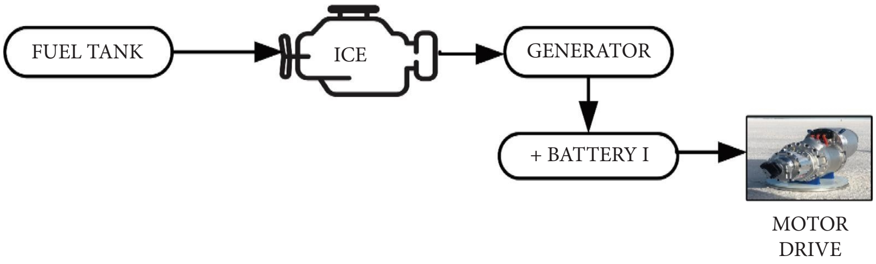


Figure 4: A simple block diagram of ER-ICE configuration.

2.1.2. Extend Range Regenerate Shock Absorber (ER-RSA). The suspension of the vehicle's primary component is a shock absorber to filter the vibrations by using suspension springs on rough roads. The heat and hydraulic friction absorb the energy from vibrational sources by shock absorbers [84]. At present, a wide variety of three RSAs are available. The linear or rotary is the scheme in operation [85]. In the first method, electric power is generated by an electromagnetic used directly. An electromagnetic induction principle will work on these to convert the kinetic energy of vertical oscillation to electricity by an RSA of linear electromagnetic.

The RSA of hydraulic is the second method. This RSA can be powered by using an oscillatory motion to run an electric power generator. Modern shock absorbers utilize oil to flow in a parallel oil circuit by replacing the existing hydraulic shock absorbers. These fluids drive the DC/AC generator parallel to the hydraulic motor [86].

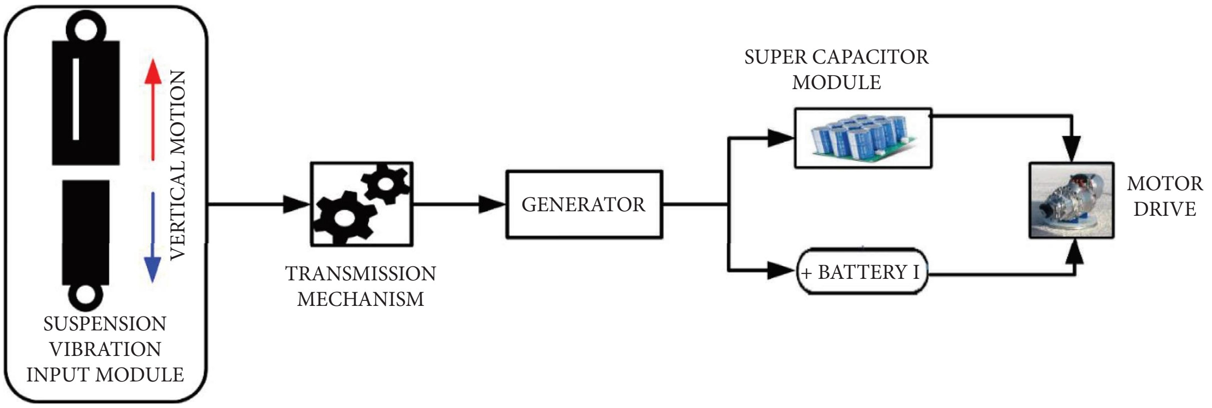


Figure 5: A simple block diagram of ER-RSA configuration.

The RSA of mechanical is the third method. It is the most efficient and has a high average power [84]. The combined architecture of RSA with the supercapacitor increases the battery lifetime enormously. The major parts are as follows: (1) the suspension vibration as input block, (2) the transmission block, (3) the generator block, and (4) a block with power storage, as shown in Figure 5.

2.1.3. Extended Range Regenerative Braking (ER-RB). The electric vehicle deceleration process leads to transmitting torque to the axle and simultaneously incorporates the charging of the battery, as shown in Figure 6. Under this condition, a kinetic energy system represented by a regenerative braking system (RBS) enhances the overall energy efficiency of an electric vehicle (EV). Two modes of the braking system are used in EVs to produce the brake torque together or in either form, namely, regenerative braking and friction braking of the system [87]. A suitable control strategy is needed to improve energy recovery and safety and reduce the loss rate. A revised regenerative braking control strategy (RRBCS) reduces the inefficiency and prolongs the battery life by increasing the maximum energy recovery and safety [88].

A transmission system with high transmission efficiency needs to improve. A hybrid braking method can improve transmission efficiency using an automatic mechanical transmission (AMT). By applying the braking force to the transmission gear system, in this condition, the speed does not affect. However, the vehicle's condition changes by the braking force and transmission gear accordingly; this method enhances the EV system's economy. Further improvement of this method needs to operate in the maximum permissible condition for maximum energy recovery. A suitable control strategy is required to improve the rate of energy recovery, stability, and safety [89].

2.1.4. Extended Range-Fuel Cell (ER-FC). A fuel cell is a device that converts directly into electrical energy and heat from the electrochemical energy conversion [90]. It incorporates to produce water and electricity by redundant oxidants in the output of the electrochemical process [91].

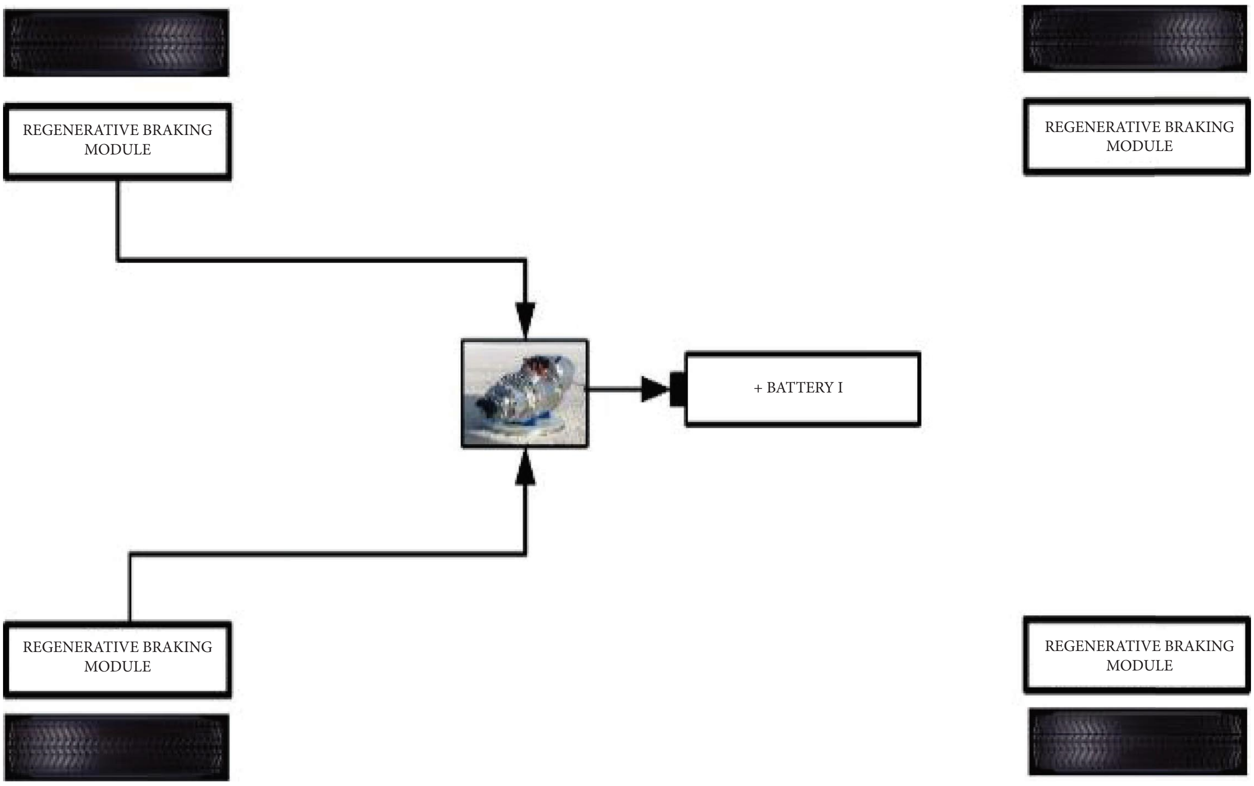
A fuel cell consists of an anode, cathode, and electrolyte, which are the primary components. In this process, the anode delivers the hydrogen, and oxygen provides the cathode [92]. With an external circuit, the positively charged particles move towards the cathode side, and the electrons or negative-ion charged particles move towards the anode to rejoin. In this process, the moment of electrons creates electricity in external circuits. Then, the combination of positively charged particles and the oxygen collision with the electrons produces heat and water, as shown in Figure 7 [18, 93–99].

2.1.5. Extended Range Microgas Turbine (ER-MGT). Microgas turbines (MGT) for small output power are in the range of 30–500 KW [100]. The major components of the MGT are a radial compressor with a single stage, a recuperator, and a radial turbine section. Four types of the process consist of an MGT cycle as follows:

(1) The radial compressor consists of inlet air, and it compresses inlet air
(2) The hot air mixed with the fuel in the combustion chamber is passed from the recuperator
(3) In the stages of turbine stages, it expands hot gas and
(4) In this process, the air compressor drives the equipment (usually the generator), and succeeding mechanical energy develops from gas energy.

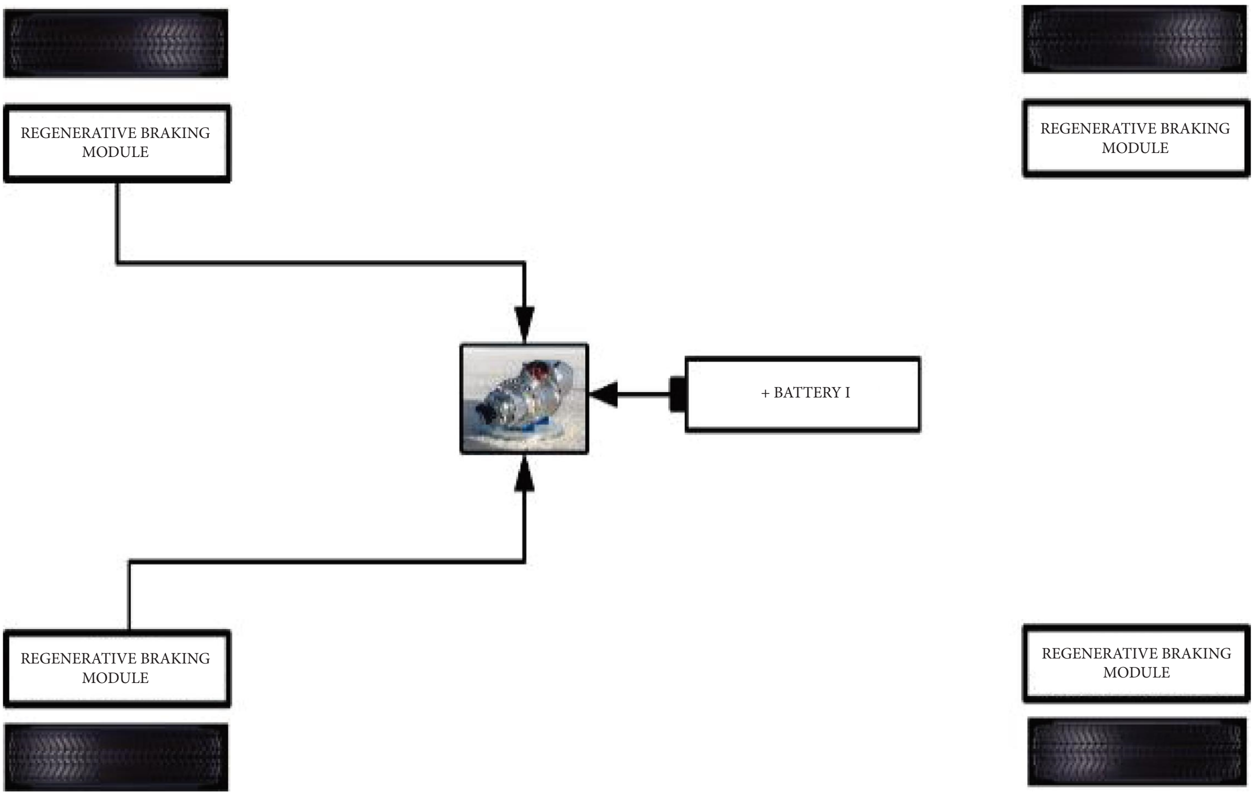
The gas turbine, according to manufacturers, represents the most effective future technology. Significantly, alternatives are needed. RE is an alternative to the EV, and MGT is an alternative to the ICE. The gaseous exhaust emissions are minimal, produced by the MGT such as carbon monoxide and hydrocarbons. In contrast, the application is more stable than the ICE. The carbon monoxide level of potential reduces [101–103]. Figure 8 shows that the battery and generator connected to MGT-ER are in a series configuration.

2.1.6. Solar Energy Storage Extended Range (SES-ER). The heat energy and electricity produced by the sunlight then cause the moment to start, flowing electrons to produce electricity in photovoltaic cells (PV cells)—automakers are



GENERATOR MODE

(a)



TRACTION MODE

(b)

Figure 6: The energy flow in ER-RB configuration: (a) generator mode; (b) traction mode.

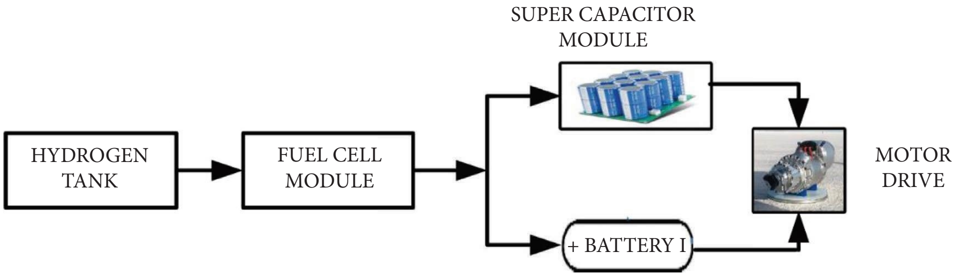


Figure 7: An ER-FC configuration block diagram.

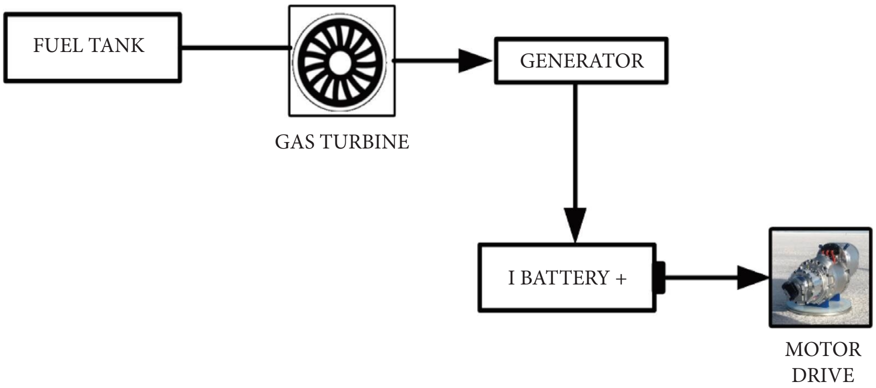


Figure 8: An ER-MGT configuration block diagram.

interested in solar energy storage (SES) systems for economic, safety view, and cleanliness. Studying systematic and lighter SES has enhanced the analysis of numerous automobile industries [104]. Integration of renewable energy sources is needed to improve the charging capacity of the EREV [105] and also reduce the overall cost-effectiveness by utilizing solar-type renewable energy sources [106] and further required to improve the storage capacity in the electric vehicle [107].

However, the charging infrastructure places a vital role in EV energy management [108]. Furthermore, it enhances the battery charging topologies and widely used methodologies in EV battery technologies [109]. In city driving, the 10% autonomy uses PVC in cars [110]. Ezzat and Dincer [111] offered modern complete energy storage solution for EREV. The proposed method incorporates batteries, PVCs, and a fuel cell (FC). The findings suggested that using solar cells makes EREV's energy storage technology more efficient. The ideal complements to a range extender. Figure 9 shows the layout of an ER-FES.

2.2. EREV Comparisons with Various Technologies. The design consideration and parameter estimation of a range-extended electric vehicle are the most critical issue in developing the technologies and their comparisons, analyzing different technologies, and analyzing the relationship of their components and configurations described in Table 2. The range extender selection criterion for the vehicle design depends upon the specific characteristics of the vehicle, and these are compared and evaluated by the following:

(i) Required power from the system;
(ii) The amount of additional range;
(iii) The system efficiency is global;
(iv) Emissions of the system.

3. Extended-Range Electric Vehicle System Design and Powertrain Classification

There are two next-generation vehicles, namely, hybrid electric vehicles (HEVs) and (BEVs). As seen in Section 1, in the battery, electric vehicle storage capacity is the primary constraint infrastructure availability for charging, design rationality of EMS, and charging speed of the battery. The first phase is many social and technical challenges.

Power conversion efficiency is higher in this structure, which requires a high energy storage system (ESS) compared to the other HEVs described in Table 1. An extended-range electric vehicle has proposed a new HEV definition in recent years. Based on long-distance driving ability, it progressed through rapid development and met the government consumption criteria for indices [50]. The best alternatives for future road transportation are widely acknowledged [25, 37, 152]. As shown in Figure 6, an EREV is a simplified topological construction.

3.1. Basic Pattern and Operation of EREV. An EREV consists of a hybrid energy storage system (HESS) with two operating modes, namely, charge-depleting and sustaining methods. The charge depleting mode maintains till the dead zone of

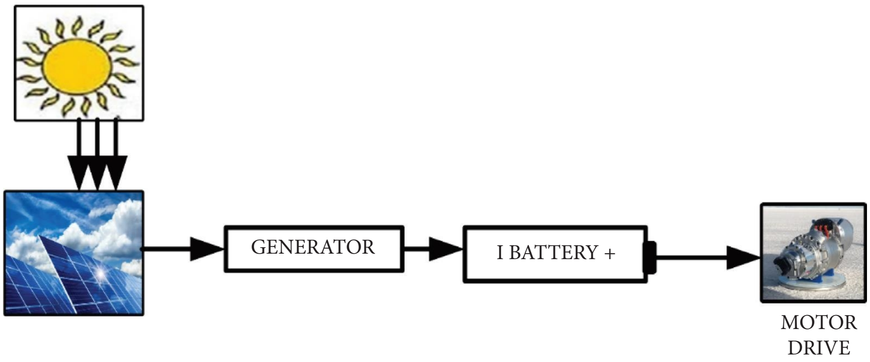


Figure 9: An ER-SES configuration block diagram.

SOC. In this mode, the ICE is disabled, and the sustaining charge mode supports the remaining SOC. This way, charge-depleting (CD) mode is reliable with less power consumption and more SOC maintained by the operating modes of a hybrid energy storage system. In contrast, if the state of charge (SOC) falls below a certain level or the power demand increases, the engine's lack of power is compensated. In this case, the APU's electric energy can power the ESS and drive the motor via power converters. Furthermore, studies show HESS power management, APU charging control, and power flow distribution [153–156]. The following sections deal with the APU control strategies and power management of HESS.

3.2. The Auxiliary Power Unit (APU). The vehicle design objective dictates the choice of an APU for EREV [157, 158] shown in Figure 10. A conventional vehicle's engine selection is quite different from EREV. Typically, a broad range of dynamic performance requires sufficient power to maintain the required speed range, high fuel consumption, and more significant displacement [37]. On the other hand, the engine selection for APU is different storage. Increasing the degree of electrification reduces the number of pistons and displacement [49]. Specially designed range extenders powered by small engines boost the electric range in EREVs since they have fewer cylinders [159, 160], to obtain minimum designing and manufacturing costs by using small displacement engines consisting of fewer materials.

As shown in Figure 11, electric energy storage will consist of two basic configurations. First, the battery energy storage system is only a part of most energy storage systems. The hybrid energy storage system achieves high peak discharge and extended battery life, and the converter topology maintains the voltage stability between the battery and the supercapacitor [51]. The smaller displacement engines will satisfy traditional engines' manufacturing and design characteristics [37]. Furthermore, the engine does not need to run over a wide speed range. A high-efficiency zone of an engine is possible for the EREV with lesser noise and lower vibrations. This way, the standard transmission is not required for the EREV power train [161, 162].

Compared to the Otto cycle, APU control strategies are higher inherent characteristics. In [159], a specially designed two-stroke engine does electric power generation in a single cylinder. In the new EREV project announced by Mazda, the range extender consists of a redesigned engine [163]. The rotor reliability and stability are maintained by the boxer engine perfectly.

3.3. Hybrid Energy Storage System with Various Energy Storage Elements. Figure 11 depicts their samples. The most basic ESS configuration is a battery-powered storage system. HESS compensates for high peak discharge, extends the battery, and reduces voltage stability by combining SC and battery using a buck-boost converter [51]. The following are the characteristics of the battery and SC.

3.3.1. Battery. EREV, like other EVs, stores electric energy as a rechargeable battery. Lithium-ion (Li-Ion) batteries and nickel-metal hydride (Ni-MH) are two types of batteries used in modern electric vehicles. Ni-MH batteries can be recharged up to 2500 times when charged to 80% depth of charge [164].

The greater energy density and high efficiency have the Li-ion batteries [165]. A strict charging control will apply constant current charging, usually regular voltage, to charge the Li-ion batteries. To simplify, we calculate the SOC of a battery pack [24], where U_{oc} is the open-circuit voltage, R_r is the internal resistance, and P_{batt} is the battery terminal power. Q_{bat} is the nominal battery capacity [24]. The Li-ion battery, charging, and discharging protect the battery from the estimate of SOC.

$$\mathrm{SOC} = \frac{\mathrm{U_{OC}} - \sqrt{\mathrm{U_{OC}^2} - 4\mathrm{R_r}\mathrm{P_{batt}}}}{2\mathrm{Q_{batt}}\mathrm{R_{tml}}}. \tag{1}$$

3.3.2. Supercapacitor (SC). The cost is the main primary effect; installing the batteries to reduce this effect is replaced by the inherent properties of supercapacitor (SC). Compared to Li-ion batteries, the supercapacitor had a longer life span and higher power density [155, 166] in the 1990s. The Mazda model's first supercapacitor application was in automotive powertrain applications to boost the restoration of retrieved energy from regenerative braking power [167]. Due to the

Table 2: An extended range of system compared with various range extender technologies.

Extended range of the system	Extra range	System power	Emissions	Efficiency
ER-RSA	Can power an 8 W lidar for 323 days or a 2 W camera for 1292 days [112]	8–40W [112] 0.74–0.78 kW [113] 19.2–67.5 W [115] 4.3 W [84]	No	70–80% [112] 71–84% [114] 33–63% [115] 87% [84] 16% [84]
ER-TAE	80% fuel consumption savings [116]	710 W [117] 1029 W [118] 58 W [114] 1.5 kW [114]	Low	33.8–38.7% [116] 30% [117] 5.4% [118] 18% [119] 16% [114]
ER-FES	50% mileage over [112] 1.17% mileage over [121]	40 kW to 1.6 MW [120] 60–101 kW [112] 1–20 kW [123]	No	60% [112] 90–95% [122] 70–90% [124]
ER-WT	Add up to 10% [125] 7.27 km [126]	2.64 kW [126] 0.1–1.1 kW [127]	Low	75% [126] 75–90% [127]
ER-PVC	19.6 km [128]	68.2–300 W [128]	No	91.2% [128] 20.2–23% [128]
ER-MGT	370 km [129]	32 kW [130] 100 kW [132] 63.3 kW [133]	Low	47.2% [131] 28% [130] 30% [132] 35% [129] 38% [133]
ER-RB	32.1–47.7% of the total recoverable energy [134] 1.18% SOC improvement in SOC [136]	14.8 kW [135] 55.75–82.66 kJ [134] 298.75 kJ [136]	No	79–94% [135] 30–60% [76] 47% [134]
ER-rotary engine	80 km [137] 321 km [140]	3.8 kW [138] 20 kW [137]	Low	73% [139] 78% [138] 77% [137]
ER-fuel cell	500 km [141] 650 km [142] 665 km [144] 594 km [144] 1500 km [146]	20 kW [141] 85–83 kW [119] 1200 W [93] 25 kW [145] 128 kW [142]	No	70% [141] 63.6–72.4% [143] 43% [93] 55.21% [145]
ER-ICE	232.79% [79] 430 km [77] 51–139 km [25] 380 km [149] 330 km [151] 676 km [150]	30 kW [77] 35 kW [78] 5.5 kW [25] 111 kW [150]	Low	20–40% [147, 148] 31% [77]

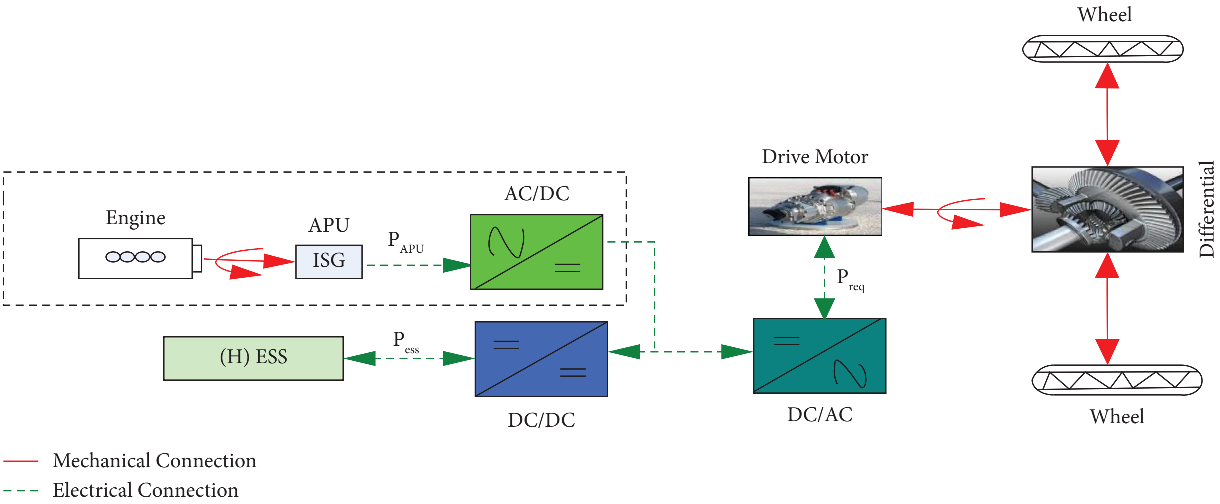
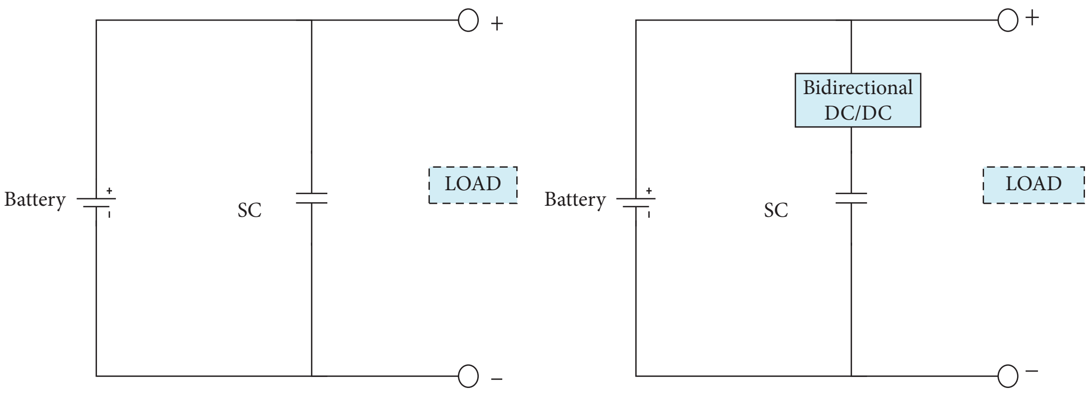


Figure 10: Overview of engine based EREV power flow.



(a) (b)

Figure 11: General diagram of an ESS and HESS; (a) ESS; (b) HESS.

lack of chemical reactions, a supercapacitor has a greater power density than a battery by charging its electrodes [168]. Supercapacitor is most suitable for fast charging and discharging applications due to its inherent characteristics, high efficiency, and low internal resistance than the battery [169]. Regenerative braking occasionally delivers a high current to the ESS, causing the battery to be damaged [170]; installing an SC can prevent this damage [169]. An SC's energy calculation equation is as follows:

$$E = \frac{1}{2}C\left(V_2^{\,2} - V_1^{\,2}\right), \tag{2}$$

where E denotes total useable electric energy, C denotes electric charge, V_2 denotes charged terminal voltage, and V_1 denotes cut-off voltage. We can see that an SC's total electric energy is proportional to its terminal voltage.

Various methods are presented in this literature to compute the supercapacitor's state of charge (SOC) [171]. Considered to be the SOC of SC is a linear relationship between calculated SOC by equation (3) with open-circuit voltage V_{SC} as follows:

$$SOC_{SC} = \frac{V_{SC}}{V_2}. \tag{3}$$

Because 75 per cent of the useable SC energy E is released when the SOC falls to 0.5 [171], SOC should be able to work within a specific range [0.5–1]. Alternatively [172], the current integral approach equation gives the SOC of SC in real-time:

$$SOC_{SC}(t_0) = SOC_{SC}(t_1) + \frac{1}{E}\int_{t0}^{t1} I_{SC}(t)dt. \tag{4}$$

4. Energy Management Control Strategies of EREV

Research topics for the EREV energy management system include control strategies for auxiliary power units and designing HESS for dynamic power management. Using SC, the auxiliary power unit can operate in high-performance mode; depending on the APU control pattern, the HESS size will also differ [173].

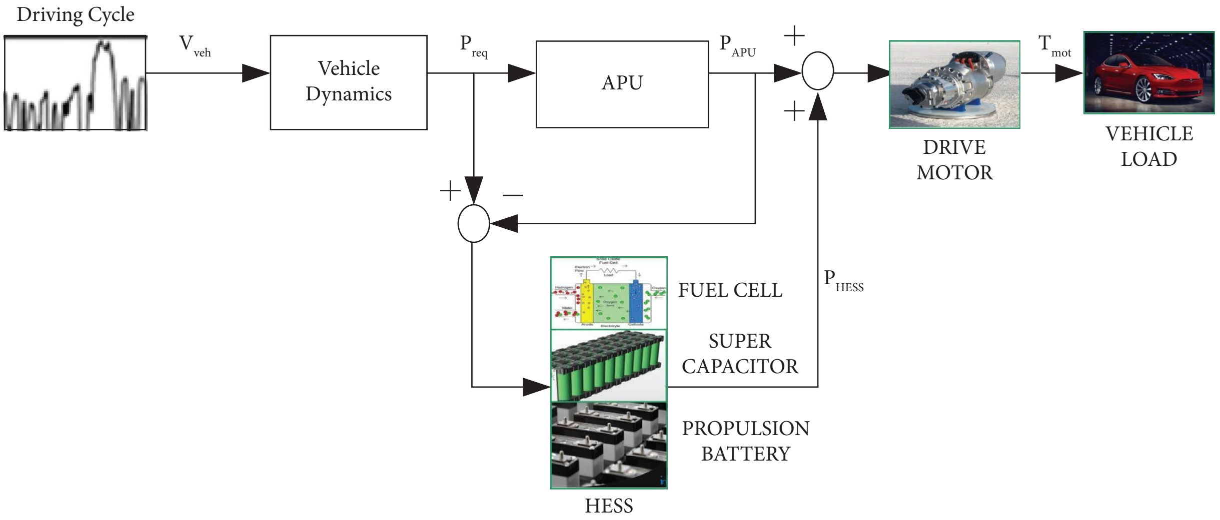


Figure 12: General diagram of a power flow strategy.

4.1. Charging Control Strategy of APU. Based on simulation and experimental findings [36, 52, 174–176], the maximum efficiency of the Proton Exchange Membrane (PEM) fuel cell and ICE is about 66% and 41%, correspondingly. The output torque and speed determine the efficiency of APU with engine-based one [177]. In contrast, a fuel cell unit's efficiency is determined primarily by its size, fuel purity, and working temperature [178]. Auxiliary power unit charging control strategies have power flow and optimal range strategies.

4.1.1. Strategy for Power Flow. Figure 12 shows the simplified diagram for the power flow strategy, even with the flexible fuel cell discharge behavior used on extended-range electric vehicles with fuel cells (FC) [179–182]. In the case of APUs powered by a combustion engine, a comprehensive, high-efficiency operating range is necessary for the engine [46, 183]. Furthermore, the intermittent power imbalance between the actual power consumption and the APU output must be considered [46, 184]. The combination of SC and HESS has minimized the errors and enhanced the power handling capacity [185].

Furthermore, a quick control convergent speed for this strategy, the driving requirements of APU, and the fuzzy logic control fulfil the power demands [186]. As a result, the fuel cell bus is a 12-hour real-world driving cycle used to estimate power requirements for HESS. The results demonstrated that a small fuel cell APU may offer the majority of the power to drive as the battery's state of charge remains high [182]. The fuel cells prior to power selection needed then thereby required charging approach of APU. On the other hand, the fuel cell efficiency achieved more than that 43% by selecting a fuel cell power range (about 65–180 kW) with maximum reliability [187]. However, the combination of ISG and combustion engine used, as APU, will give rise to high fuel usage.

This author created a slot-PM-aided generator under variable conditions with a combination of a combustion engine and a generator. The simulation outcomes revealed that the DC-excited structures are being lesser power density when compared to the slot-PM-aided generator, almost double [188, 189]. An energy management design is based on an adapted online drive cycle/power predictions by introducing the approach of Through-The-Road (TTR). High efficiency depends upon the total power consumption of APU, followed by torque [100, 122]. While protecting the end-state SOC, which could minimize the energy input consumption, the hardware-In-Loop (HIL) test disclosed that hydrogen consumption in the traditional power-following method is 8.99 per cent more than in the online strategy.

Furthermore, these authors used various strategies; in the charge sustaining (CS) stage, the battery and APU power distribution have been selected. Different methods were applied using pseudospectral optimal control (SOC) and DP [46]. The efficiency of energy improvements is carried out in [17, 50]. An ideal economic curve was selected by an engine, in the selection process, which provides the power to the powertrain by an APU.

4.1.2. Strategy for APU Optimal Range. A strategy in good range maintains APU with high fuel efficiency. Energy conversion efficiency is more if every engine supports the optimal range. As a result, this strategy configures the engine to operate at all times within an operating range or some fixed optimized points. For example, we consider the auxiliary power unit in [24]. High efficiency maintains by three operational points; the backup power is used to charge the ESS by turning on the APU. Figure 12 [153–156] depicts the appropriate engine operation range. Before selecting, a logic diagram shows how to choose the proper engine operation range using this strategy in Figure 13 [189]. To find out the battery condition and the transient power required, we perform calculations of a series type. The best range is possible by limited engine operation and a nonlinear charging strategy.

Scholars now use machine learning and mathematical approaches to develop range optimization strategies [190]. The system can adjust to an uncertain operating

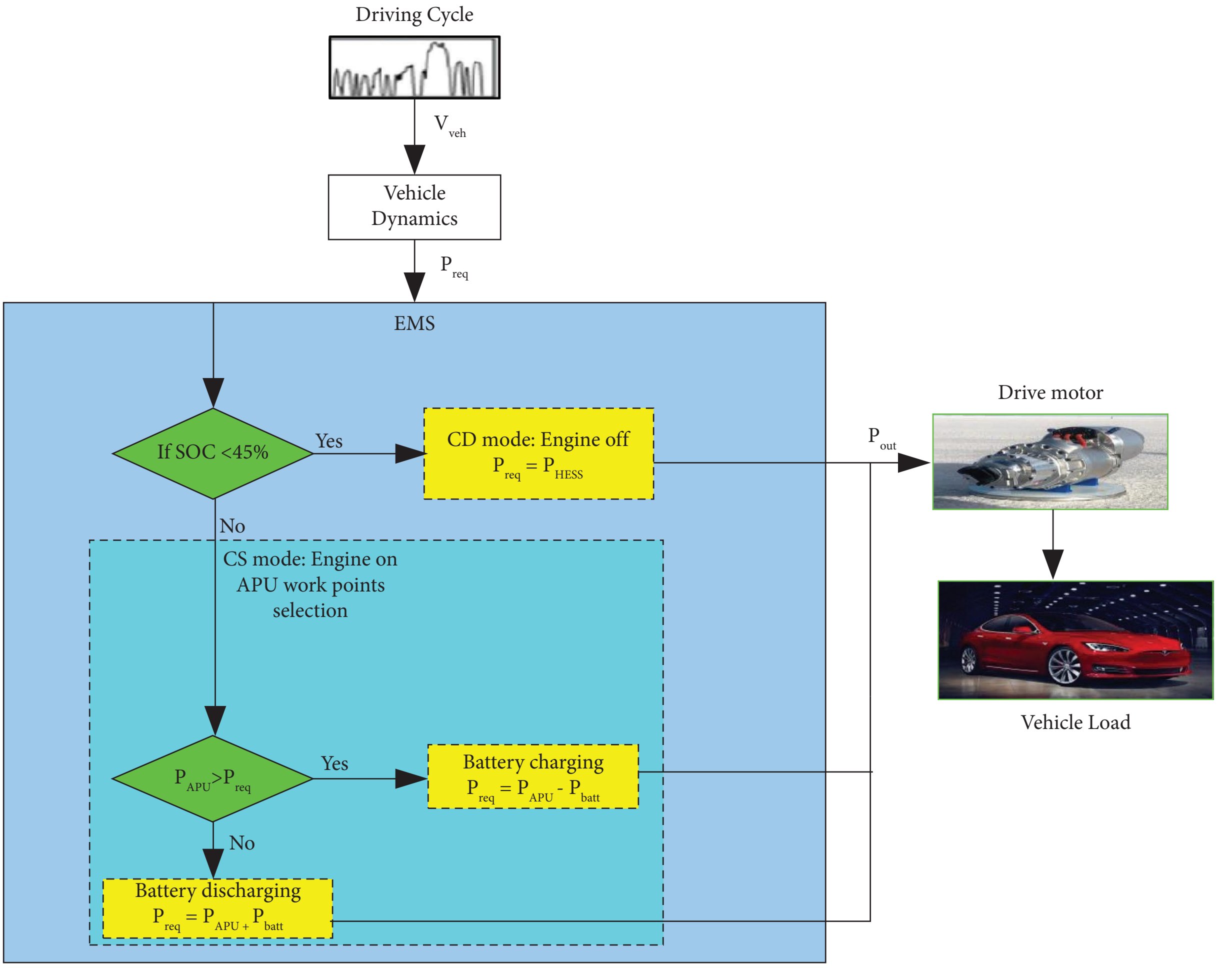


FIGURE 13: Logic diagram for optimal control strategy [189].

environment using machine-learning methods. A genetic algorithm was used in [191]. A genetic algorithm will increase engine efficiency by training and testing data based on injecting time optimization on a diesel engine.

To investigate the efficiency of a 3-cylinder Atkinson engine using an artificial neural network for APU charging, optimized engine operating points led to a high efficiency of 40.2 per cent. According to the results [135], in [192], the distance of the gas station and battery SOC are two inputs trained and led by a neural network controller design [193] to predict the engine-battery interactions and drive behavior by stochastic model predictive control (MPC). The driving style and traffic conditions influence the engine-battery power ratio. Furthermore, the optimal range strategy depends upon the PSOC and DP algorithms [46]. Here, the object is used as the actual power demand.

4.1.3. Comparison Analysis of Two Strategies. The power-following approach minimizes the power error between vehicle power required and APU output by reducing the size of an EREV and ESS. Because of the current research activities on these strategies in the APU charging control area and developing real-time experiments with HIL, there may be an opportunity to create new methods. In combination with HESS shown in Figure 14 [153], the engine or fuel cell of the vehicle will start to output power as it reaches its best performance levels. The required drive power for an EREV discussed is as follows:

The strategy must be redesigned [154]. Furthermore, the hybridization of HESS and APUs must achieve this level of performance. It aims to combine many more modern HESS architectures for power management in [194]. A HESS power management designed with three system-level objectives in this article as follows:

(a) To improve the battery life span by reducing the excessive amount of charging/discharging; (b) by utilizing the fast discharging and charging capability of the supercapacitor; (c) HESS sizing should improve to reduce weight and cost. As a result, a multiobjective optimization problem can be solved more effectively with dynamic power management classifications. Using advanced machine learning methods for continuous improvement will be necessary for the future of functional HESS power management. The operation requires multiple input signals. For example, reinforcement algorithms such as PPO, DPG, and DDPG have received widespread attention [195, 196], and HESS can provide continuous signals for data acquisition during training.

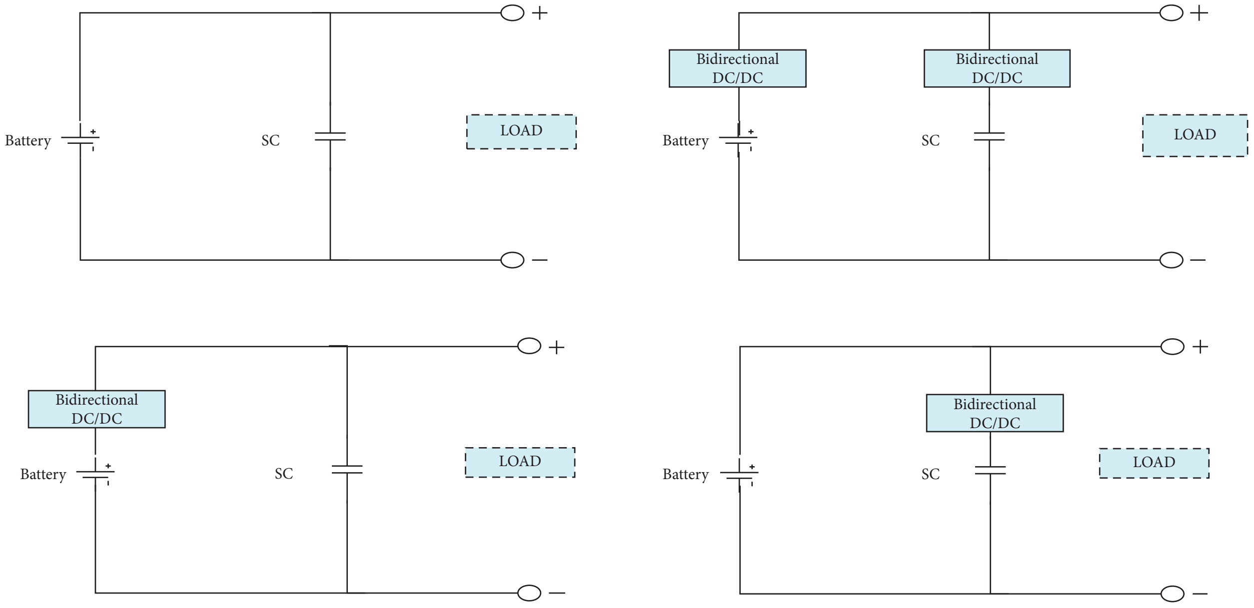


Figure 14: Widely used HESS topology structure [153].

Figure 15: The concept of the Chevrolet volt-based model [197].

5. A Specified EREV Case Analysis

The Chevrolet Volt chosen has been on the market for over a decade in this case, because it is one of the most representative EREVs. Initially, the prototype is Figure 15. The first-generation Chevrolet Volt had a 55 kW ISG, a 63 kW engine with an APU, and a 16-kWh battery pack, resulting in a maximum distance of travel of 620 km. As an outcome, the peak trip length is 620 km [198–200]. The maximum trip range was achieved to 680 km by the added features of the second generation with the compact power coupling system, a new coupling planetary gear, and a slightly large battery pack [200]. In an electric mode of operation, the traction motor delivers a power output of 111 kW [194].

5.1. On-Road Testing and Validation. Governments and agencies have proposed some initiatives to assess the capability and relevance of long-range electric vehicles, and the Chevrolet Volt was tested on the road. Energy consumption and travel range are the test subjects. A Chevrolet Volt can travel 55 km on pure electric power alone (163 miles), which is significant. This strategy enables the APU to be useful for longer travel distances through energy management. A comprehensive investigation of charging and driving for 923 test targets across 7.6 million kilometers was conducted at Idaho National Laboratory in 2013 [199]. Among the studied sample, the average daily travel distance was 65.5 km, and the average number of charges was 1.46. As a result, the Chevrolet Volt can only cover a travel distance of 73% in the EV mode if the vehicle leaves the garage with a fully charged battery.

APU will turn on the extended-range mode when the Chevrolet Volt's battery SoC falls under 17% [185]. By default, the Chevrolet Volt's charging strategy is to charge the APU and battery by utilizing the remaining energy to charge the APU. To a higher level, the battery will receive all its power [201]. The new planetary system in the Chevrolet Volt's second generation enables a new extended-range

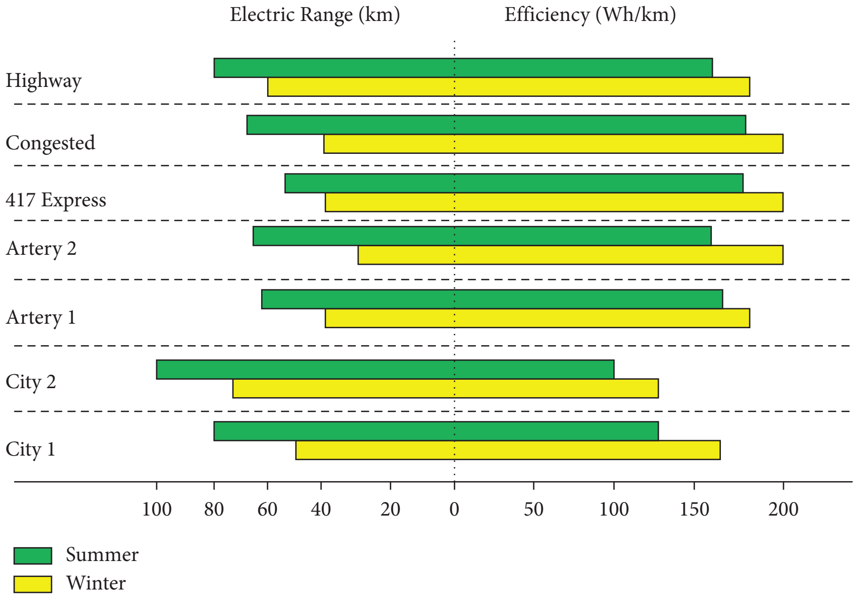


Figure 16: Shows Chevrolet volt Wh/km and average travel distance for different seasons [204].

Table 3: Various energy storage performance and a specification comparison table with the effect of cost.

Energy element	Efficiency of energy (%)	Lifespan (cycles)	Energy specification (Wh/kg)	Market price (US$/kW)	Density of power (W/kg)	Literature
PEMFC	45–66%	2500–5000 hrs	—	40–53	1000–1600	[172, 177, 178], [208–210]
Li-ion	85–95	2000	180–300	100–150	1000–3000	[211–213]
SC	>95%	1M	4.1–6.0	33.5–43.6	10,000–14,000	[166, 169, 205, 206]

mode. To improve power train efficiency by linking with the engine and ISG, validation of the model in [185] revealed that the cut-off fuel of the engine was only when the vehicle speed exceeded 65 km. By restarting the engine at higher speeds, consumption of energy is very low. According to the experiment results, the engine only operated at 25 to 35 kW.

For an EREV to be energy efficient, its operating temperature significantly impacts [197, 202]. Several studies have been conducted on the Chevrolet Volt at low temperatures to study its impact [202]. Engineers tested the Chevrolet Volt in Idaho to see how the cold climate affected the APU and discovered that the APU operated regardless of the ambient temperature when the battery SOC was below −2.8°C.

They also discovered that the cabin temperature varied based on the climate control system, caused by the average temperature of −26.1°C and the fuel consumption falling below 47 mpg (5 L/100 km). Based on a Canadian environmental study [203], the energy consumed to heat the cabin in winter is much higher than the amount consumed to cool it down in summer. In one driving cycle, CD on-road results indicated that heating the cabin consumed 4.3 kW at 1.6°C, while only 1.4 kW at 36°C. Furthermore, when the APU is switched off, the cabin is conditioned and runs in pure electric range. Figure 16 shows the energy range data on season [203]. The maximum distance is only possible by 103 km at 27°C, which is a slightly higher temperature when compared to the minimum distance of 5°C, which is 41 km, as shown by the results.

The supercapacitor characteristic differs with the same as that of a battery. The power density will be extremely high, ranging from 10 to 14 kW/kg [205, 206]. Because of its high cost and small energy storage capacity, it is not acceptable as a primary source. Nevertheless, the cost analysis constructed between market raw materials and the hybrid energy storage systems [203, 207–209] is changing slowly. In 2018, the lowest price per kilowatt was $33.50/kW, as shown in Table 3, far less than its early-twentieth-century pricing. As a result, it is still expensive in contrast to the price of Li-ion batteries, the total cost of operation (TCO). It has become more economical to pair a smaller-size SC with a battery pack to conserve the battery state of health (SOH) [166, 169, 205, 206].

6. Conclusion

This paper aims to summarize and address energy management strategies of the electric vehicle, the state-of-art of electric vehicles, and the ranging issues engineers, and researchers have tested and proven the design rationality. First, this paper provided a brief overview of the types of regenerative braking, EREV structure, and energy management, emphasizing various control strategies. APU charging strategies are described here as optimal range and power following, and discussed pros and cons shared these two in detail. The factors influence the APU's charging patterns, vehicle speed, battery SOC, and power command. In addition, it illustrates how manufacturers will easy to implement rule-based strategies.

Nevertheless, all other methods that optimize and learn data patterns that use machine learning are particularly inapplicable to commercial vehicles. Essentially, an efficacious power management system is well-designed. In addition to extending the HESS lifetime, it will save installation space and provide adequate power output. The Chevrolet Volt examined its road and energy management and performance. Finally, future EMS development for EREV will improve power train efficiency and overall system stability; novel algorithms and hardware implementation are used to overcome range anxiety and deal with electric vehicle energy management.

Abbreviations

APU:	Auxiliary power unit
BEV:	Battery electric vehicle
CD:	Charge-depleting
CS:	Charge-sustaining
CO:	Carbon monoxide
CO_2:	Carbon dioxide
EMS:	Energy management strategy
EREV:	Extended range electric vehicle
ESS:	Energy storage system
FC:	Fuel cell
H_2:	Hydrogen
HESS:	Hybrid energy storage system
HEV:	Hybrid electric vehicle
HIL:	Hardware in the loop
ISG:	Integrated starter generator
Li-Ion:	Lithium Ion
MPC:	Model predictive control
Ni-MH:	Nickel-metal hydride
PEM:	Proton exchange membrane
PHEV:	Plug-in hybrid electric vehicle
SOC:	Pseudospectral optimal control
SC:	Super-capacitor
SoC:	State-of-charge
SOH:	State of health
TCO:	Total cost of ownership
TTR:	Through-the-road.

Data Availability

No data were used to support the findings of this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Shana Lakshmi Prasad helped in conceptualization, methodology, writing-original draft preparation, visualization, and investigation. Abhishek Gudipalli helped in sSupervision, validation, and writing-Reviewing and Editing.

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